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MEMS-BASED RESEARCH IN INTEGRATED MONITORING AND ACTUATION AT CASE WESTERN RESERVE UNIVERSITY

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Abstract: The paper discusses the development of MEMS at CWRU for the active monitoring and control of systems or structures. The ultimate objective is the realization of high density array architectures of microfabricated sensors and actuators for distributed monitoring and control of a system or its components. Our program addresses the research needs for the advancement of the technology toward realization of low-cost, reliable, integrated sensor/actuator devices and arrays capable of real-time signal processing and control. Our program is also addressing the need for high-temperature MEMS required for use in many aerospace, automotive, and industrial process control applications. Toward this goal, we have research and development activities in high-temperature sensors and actuators made from silicon carbide (SiC), a wide-band-gap semiconductor material capable of functioning in environments where the ambient temperature is well over 250 C, which is the limit of silicon devices. We are also investigating high-phase transformation temperature shape-memory alloys as integrated actuation mechanisms suitable for various high-temperature applications.

Key Words: Microelectromechanical Systems; MEMS; microsensors; microactuators; microsensor arrays; high-temperature microsensors; high-temperature microactuators.

Introduction: As a elemental material, single-crystal silicon has probably been better characterized than any other material known to man, mainly due to the commercial interest of the integrated circuit (IC) industry. The electrical properties of silicon have been exploited to create several large and successful industries. However, silicon is also an excellent mechanical material with a yield strength twice that of stainless steel and a strength-to-weight ratio exceeding that of aluminum. Silicon has a higher modulus of elasticity than steel, yet one-third its density [1]. The excellent mechanical properties of silicon combined with the high sensitivity to external and environmental factors allows it to be used successfully in various microsensor and microactuator applications.

The ability to fabricate micromechanical elements such as microsensors and microactuators from silicon has inherent benefits which make the technology extremely attractive from a manufacturing perspective. Silicon micromachined sensors and actuators can be made using the same techniques of the integrated circuit industry and several important consequences result from this technological leveraging: the ability to batch fabricate; and the existence of the very sizable integrated circuit infrastructure.

Another important benefit of making sensors and actuators from silicon is that the sensor and actuation elements can be readily merged with integrated circuits to form microelectromechanical systems or MEMS. In the most general form, MEMS is the merging of sensors, actuators, and electronics onto the same silicon substrate. The sensors provide information about the environment based on electrical, physical, chemical, or

biological measurements; the electronics process the information derived from the sensors and provide a decision making capability for the system based on this processed information; and the actuators respond to control signals from the electronics and manipulate the system or environment for a desired outcome or purpose. While integrated circuit technology has brought unprecedented computational power ever closer to the point of use, revolutionizing the design of electronics products and enabling the creation of entirely new product categories, MEMS promises to do the same for electromechanical systems through miniaturization, batch fabrication, and integration with electronics, thereby enabling the development of smart systems by providing the required interface between the available computational power and the physical world through the perception and control capabilities of microsensors and microactuators.

MEMS technology is expected to have enormous opportunities in the commercial markets due to the low-cost, high functionality, and small size/weight of the devices. MEMS technology allows much more functionality to be placed within a given space than conventional technologies. Alternatively, sophisticated functionality can be placed where it never could be placed before. For the last two decades, researchers at various university, government, and industrial labs having been working on silicon micromachines and silicon micromachining technology mostly in the form of discrete sensors or actuators. The fruits of this research are evident by a rapidly growing and vibrant industry which currently has annual components sales estimated to be in excess of one billion dollars and several tens of billions of dollars in value-added products made possible by the technology. MEMS devices are emerging as product differentiators in markets such as automotive, aerospace, industrial process control, electronics instrumentation, office equipment, appliances, and telecommunications. Research is now focused on merging the sensors, actuators and electronics onto silicon substrates to realize fully integrated smart systems. As research in this area progresses, the world market for MEMS is expected to reach fourteen billion dollars by the year 2000 with an additional one-hundred billion dollars in high-value added product sales [2].

At CWRU, we are addressing the development of MEMS, embedded into structures or mounted onto structural surfaces, for the active monitoring and control of static and transient phenomenon. Our program addresses the need for the advancement of technology toward realization of low-cost, reliable, high-density, integrated sensor/actuator devices and arrays capable of real-time signal processing and control, while also addressing the need for high-temperature MEMS required for use in many aerospace, automotive, and industrial process control applications. This paper will review current research program at CWRU in these topic areas.

Embedded Tire Sensors: Devices enabling improved monitoring of tire air pressure are of interest to trucking and insurance companies since the maintenance of correct air pressures results in increased fuel economy, improved tire wear, and a higher level of highway safety. The preferred method of employment is to mold the pressure sensing device and associated readout electronics into the truck tire during manufacture and then remotely interrogate the device using a mobile or fixed telemetry unit. A particularly important requirement of the sensor is its stability over extended periods of time, since recalibration of the device after insertion into the tire is difficult. Another difficult requirement is the ability of the sensor and electronics to withstand the harsh pressures and temperatures of the tire molding process.

The embedded MEMS tire air pressure sensor program originated out of research at CWRU on devices for highly-stable, long-term continuous measurement of intra-cranial pressure in hydrocephalus patients by Ko [3]. Leveraging this technology, CWRU researchers in joint

cooperation with Goodyear Tire and Rubber, have developed a smart tire pressure sensor [4]. The embedded MEMS tire air pressure sensor is a low-cost, easy-to-use, and fast method for the continuous measurement of truck tire air pressures. The sensor is embedded in the tire sidewall during manufacture and remotely interrogated using either a handheld or fixed telemetry unit. A capacitive-based sensor is employed for the pressure measurements in order to take advantage of the higher sensitivity, higher stability, and larger dynamic range capacitive pressure sensors exhibit over competing technologies. The sensor consists of a bulk micromachined deformable thin silicon diaphragm which acts as one electrode of the capacitor (Figure 1). The silicon is anodically bonded to a glass substrate having a metal electrode on the surface, thereby forming the other capacitor plate. As the deformable thin silicon membrane deflects under pressure loading, the membrane deflection results in a measurable change in the capacitance. The change in capacitance is converted to an output voltage over a dynamic range of 0 to 80 psig. The extremely small size of these devices (e.g., 2mm x 2mm x 1mm) allows them to be embedded into a tire during manufacturing to provide life-time tire pressure monitoring capabilities.

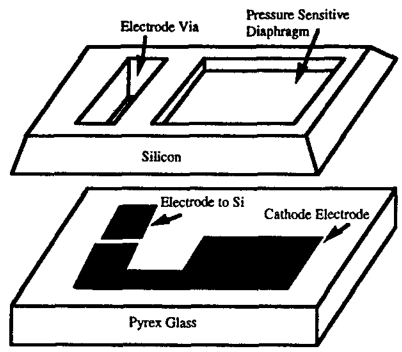

Figure 1. Illustration of the silicon micromachined CWRU embedded truck tire pressure sensor [4].

Microfabricated Shear Stress Sensor: The measurement of shear stresses is of primary importance in the design of aerodynamic and hydrodynamic components since it determines a major part of the drag and has significant influence on many of the performance characteristics. Further, as progress advances on aircraft employing non-fixed airfoils for active wing positioning, continuous measurement of shear stress may become desirable. Several indirect methods for the measurement of wall shear stress have been developed including, the Preston tube, hot wire/films, and liquid surface techniques. However, no universal method for the accurate and direct measurement of shear stress has yet been realized.

A microfabricated sensor enabling the direct measurement of wall shear stress has been developed at CWRU [5]. Both active and passive designs have been demonstrated, and integration of the sensors with on-chip electronics is pursued. Furthermore, in a collaboration between CWRU and Analog devices, Inc., Waltham, MA, integrated shear stress sensors have been produced which combine surface micromachining with a 3 µm BiCMOS process. These sensors have the transducer element and electronics for signal amplification and conditioning integrated on the same chip. The CWRU device employs a surface micromachined polysilicon floating element, of dimensions 100µm x 100µm, suspended by 100µm-long polysilicon tethers separated from the substrate surface by a micron-sized air gap (Figure 2). The floating element displaces laterally when loaded by the force of a flowing fluid, and this displacement is measured by the change in capacitance between the element and interdigitated sensing electrodes. In the passive device, the

floating element displaces in response to the fluid flow, and this displacement is detected by a differential capacitive transducer. In the active device, an electrostatic drive is used to restore the floating element to its null displacement position, thereby improving the sensor performance. Microfabrication of the device in silicon enables an fully integrated active sensor to be realized having capability for self-testing and self-calibration, and thereby improving long-term reliability and stability.

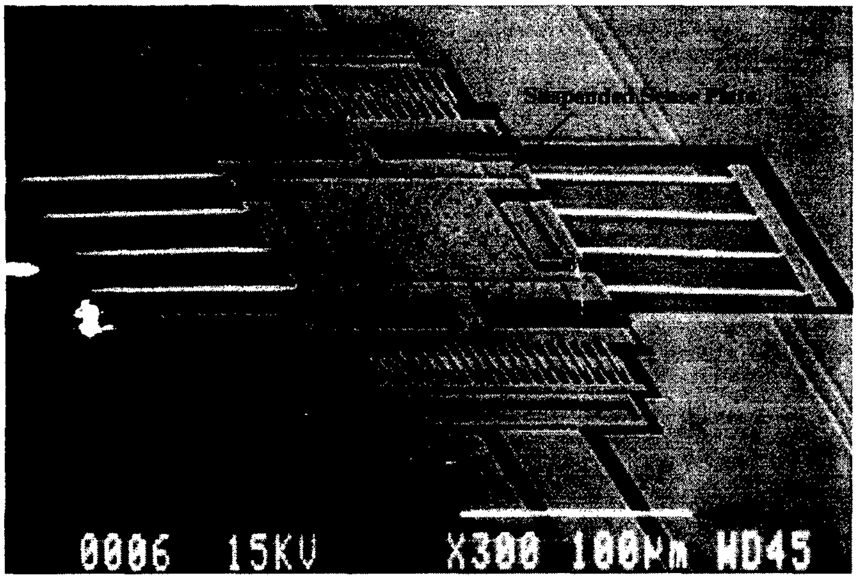

Figure 2. SEM photo of the transducer element of the CWRU shear stress microsensor.

The graph in Figure 3 shows test results for a sample of shear stress sensors. Sensors with 100µm and 120µm folded beams were tested, illustrating that the sensitivity of the sensor can be tailored by varying the stiffness of the suspended support structure. The suspended plate with the longer support beams is more compliant, exhibiting a higher sensitivity to shear stress. Separate data points indicate test results of different sensors, showing that a similar response is achieved from one sensor to the next. Testing of the integrated CWRU/Analog Device sensors demonstrated an electrical sensitivity of 6 Pa/Volt. The first resonant frequencies of the transducer elements was near 10 kHz.

Smart Microvalves: The ultimate goal of the miniature valve project is to develop "intelligent" or "smart" microvalves and microvalve arrays. Our work on smart microvalves and microvalve arrays is focused on two application areas based on the interest of our commercial partners, combustion-engine fuel delivery systems, particularly gas-turbine engines, and closed-loop control drug delivery systems. However, it is expected that the results of this work will positively impact many other application areas as well.

The smart microvalve consists of a micromechanical fluid valve (for liquids and gases), along with associated flow sensing and integrated electronics for closed-loop feedback control of the fluid delivery rate. The microvalve employs an electrically-activated, fully-integrated, shape-memory alloy actuation mechanism, thereby enabling the valve to generate sufficient actuation force to control fluid at pressures typical for fuel delivery systems, while simultaneously achieving a sufficiently large stroke thereby reducing the open flow resistance to liquids. An important aspect of our development is fully-integrated,

electrically-activated, arrays of smart valves for redundancy, spatial flow control, and macro flow control with microactuators, all of which are required for intelligent fluid management and distribution. Further, we are exploring technologies enabling the smart microvalve to function in extremely harsh conditions, such as high temperatures and corrosive environments which are common to many fuel distribution applications. For low-temperature (below 100 C) operation, we are using TiNi shape-memory alloy for the valve actuation. For higher temperature applications, we are investigating a high phase transition temperature shape-memory alloy technology, such as TiPdNi. We are also exploring the use of SiC to coat valve seats and internal chambers. These improvements are expected to reduce sticking and wear of the valve seat during cycling, as well as allow the microvalve to operate in corrosive environments.

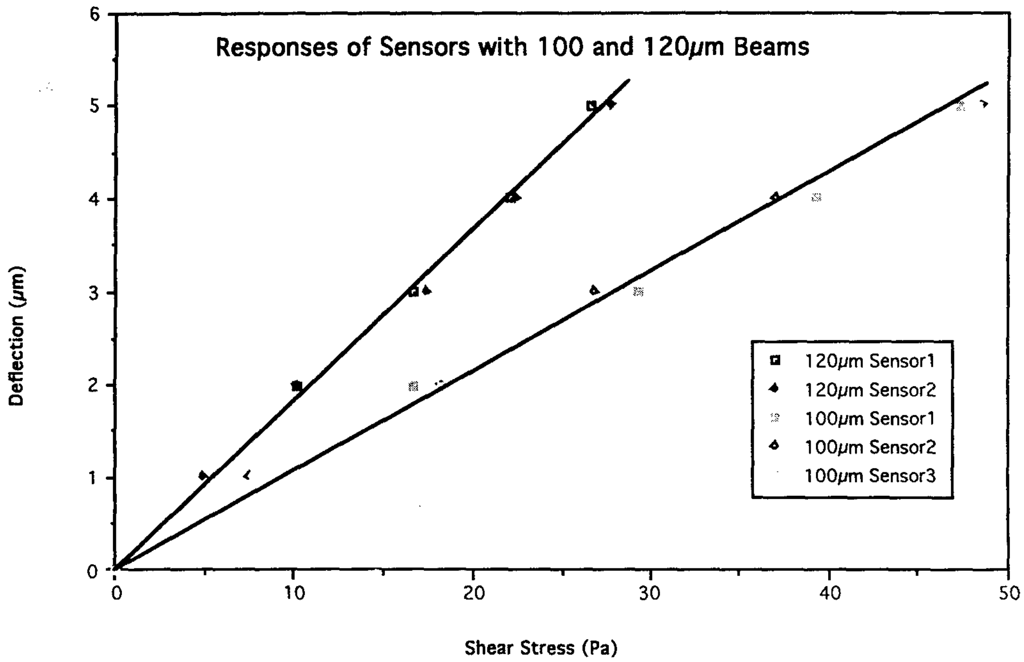

Figure 3. The element deflection as a function of applied shear stress is indicated for three sensors with 100μm-long and two sensors with 120μm-long support beams. The sensors with longer beams are more compliant, resulting in a greater sensitivity.

Currently, our TiNi films are rf sputter deposited in an ultra-high vacuum chamber, using a 2-inch TiNi target [6]. The films are amorphous as-deposited at room temperature. Therefore, an anneal at 520 C for 30 minutes, is performed directly after deposition, without breaking vacuum, in order to crystallize the films. The crystallized TiNi films display good shape memory behavior, with phase transformation temperatures around 60 C and temperature hystereses as low as 10 degrees. The transformation is between the austenite and martensite phases, which will achieve the maximum recovery force. We have recently purchased a pulsed-laser deposition (PLD) system. This system will employ two lasers, whose powers can be determined independently, thereby enabling very precise control over the relative deposition rates of the two elements and the resulting shape-memory behavior. The resultant thin films of TiNi are expected to have uniform thickness and very well controlled composition (e.g., to within 0.1 at %). In addition, this new

system will allow deposition over a four inch diameter area, and since no ambient gases are used, the resulting films will contain less impurities.

A conceptual drawing of one of the microvalve designs we are developing is shown in Figure 4. To fully exploit the large strain levels possible with the use of shape-memory alloys, the deformable part of the actuator mechanism must consist entirely of TiNi, since a silicon diaphragm would fracture at strains larger than 0.5%. The design uses a TiNi diaphragm completely released from the silicon substrate in the area of the valve chamber. Consequently, the stroke of the valve is limited only by the maximum strain level of the shape-memory alloy. Resistive heating of the TiNi will be used to initiate the martensite to austenite phase transformation causing the plunger to lift off of the outlet orifice as the material recovers its initial shape and actuating the valve. Closure of the valve is achieved by turning off the heating power, allowing the TiNi to cool. As the TiNi cools, it once again returns to the more compliant martensite phase. The silicon spring applies a reset force on the TiNi layer causing the plunger to reseal over the outlet orifice.

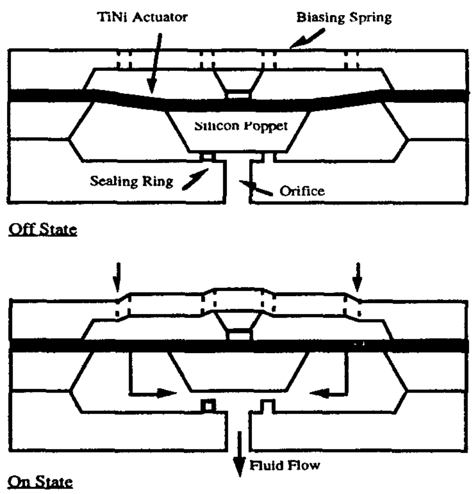

Figure 4. Shape-memory alloy actuated microvalve employing integrated silicon reset spring.

Silicon Carbide (SiC) MEMS: Our program at CWRU is developing silicon carbide (SiC) as a basic mechanical material for high-temperature (e.g., up to 550°C) MEMS. We recently built a cold-walled SiC APCVD reactor for the deposition of single-crystal 3C-SiC onto 4 inch substrates which has been fully operational for about one year (Figure 5). High quality single-crystal SiC films are routinely deposited in the reactor with good uniformity onto 4 inch substrates [7]. Augmented with these in-house capabilities for SiC deposition, our approach is to move many of the concepts from the integrated silicon-based MEMS technology onto SiC. The high-temperature sensor devices we are currently exploring include; pressure sensors, temperature sensors, and flow sensors. We are also investigating the use of SiC coating to improve the wear properties of silicon micromechanical elements and SiC-based microactuators.

The cornerstone of our effort is the development of a MEMS-based, in-cylinder pressure sensor for engine monitoring using SiC. The design for the first prototype of the micromachined SiC pressure sensor utilizes ion-implanted SiC piezoresistors fabricated on a SiC bulk-micromachined diaphragm. The fabrication for this device is nearly complete.

We are also extending our current SiC surface micromachining capability toward an integrated high-temperature MEMS process based on SiC surface micromachining on SiC substrates. To do this, we are using many of the already established technologies in SiC electronics to develop an integrated MEMS technology on SiC. The SiC surface micromachining process enables the fabrication of sealed-cavity, capacitive SiC pressure sensors, as well as lateral-resonant-type devices suitable for high temperature applications.

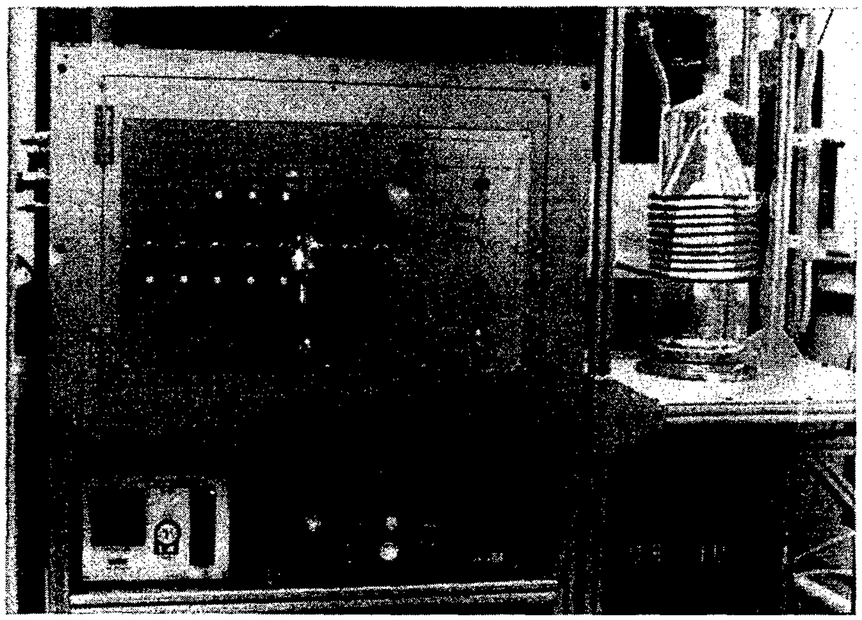

Figure 5. Picture of the APCVD SiC Reactor.

Using a SiC surface micromachining process, we recently fabricated a poly-SiC lateral-resonant-type electrostatic microactuator [8]. After growth of the poly-SiC on polysilicon, a 5000Å-thick aluminum masking layer was deposited, patterned, and wet-etched. Next, with the patterned aluminum layer as the etch mask, poly-SiC microstructures were defined by reactive ion etching in a CHF_3/O_2 mixture. After etching, the aluminum mask was removed using HF. The poly-SiC microstructures were then released by etching the polysilicon sacrificial layer in 40 wt% KOH at 40°C. The etching time is controlled so that the polysilicon was etched from everywhere but under the anchor regions of the poly-SiC devices. Figure 6 shows an SEM image of a released lateral resonant microactuator fabricated using the above-mentioned process. Devices with lateral dimensions as large as 500 μm were fabricated, with no noticeable residual stress induced deformations. The resonant frequencies of the nominally 2 μm-thick poly-SiC microstructures ranged from 20 kHz to 60 kHz, depending on the geometry.

Integrated Optical Switches: A novel variation of micromotor technology was recently developed at CWRU, the diffraction grating microscanner [9]. The diffraction grating microscanner is potentially a low-cost, highly reliable and small sized integrated optical scanner which may have many advantages over conventional electromechanically rotated optical prisms or grating commonly used in optical switches, bar-code label laser scanners, and computer interconnects. The diffraction grating microscanner is shown in Figure 7. A diffraction grating is etched in the top surface of a solid micromotor rotor using dry plasma etching. The microscanner uses a relatively thick polysilicon layer to form the diffraction grating rotor. This was necessary because the diffraction grating required a

relatively deep etch in the top surface of the rotor and the drive voltages must be relatively low. The increased thickness of the motor poles and the rotor allows for increased electrostatic coupling and therefore reduced drive voltages. The microscanners have a minimum operating voltage of 18V and operate at scan speeds over 5000 rpm. The devices have over one meter of working distance, and the diffracted beam profiles are of high quality.

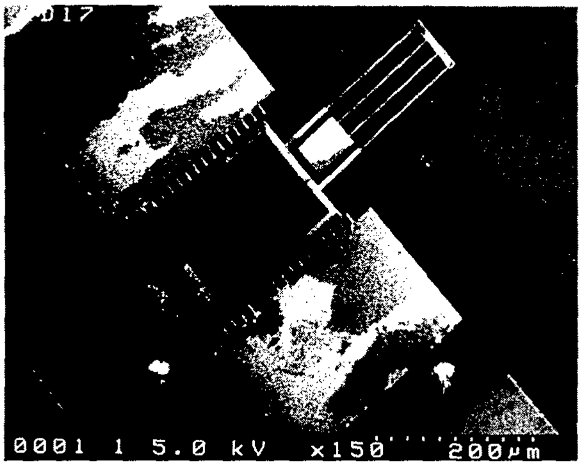

Figure 6. SiC surface micromachined lateral resonant actuator.

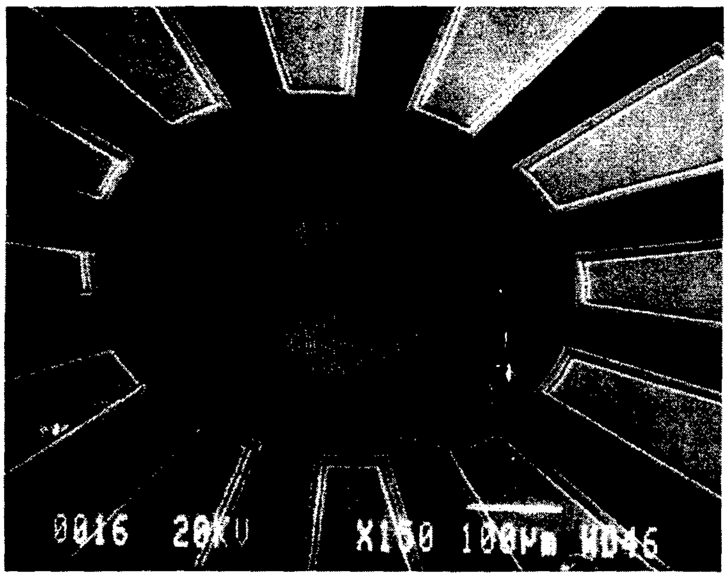

Figure 7. SEM of the polysilicon surface micromachined diffraction grating microscanner.

Micromechanical Relays: Micromechanical relays have many applications in communications, power distribution, and industrial control. Micromechanical relays have several advantages over conventional mechanical relays including: smaller size; faster

response time; low-cost; and lower power. Furthermore, micromechanical relays, unlike solid-state relays, have no leakage, are more rugged, and can handle larger signals. A micromechanical relay developed at CWRU is shown in Figure 8 [10]. The device was fabricated by electroless plating of nickel in a micromold pattern formed in a relatively thick positive photoresist layer. A standard UV exposure combined with a highly transparent and viscous resist (Hoechst AZ 4620) allows a 3.5 μm linewidths with 2.5 μm spaces to be formed in resists layers 25 μm thick with a high aspect ratio. The CWRU micromechanical relays have a measured contact resistance of 10 ohms, can handle current loads over 150 mA, and have a switching bandwidth over 1 kHz.

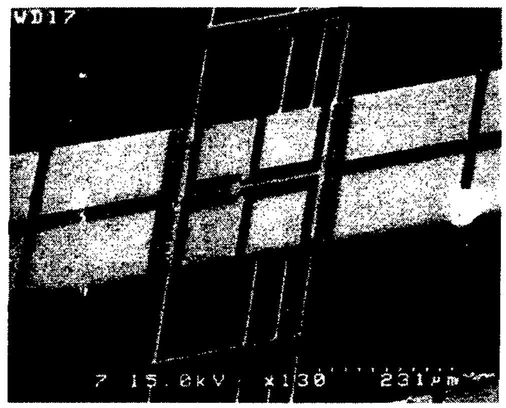

Figure 8. SEM of the CWRU micromechanical relay.

Conclusions: MEMS technology promises to radically change our capabilities in the design and implementation of systems and products requiring sensors and actuators. The low-cost, high performance and high functionality of MEMS compares extremely well with conventional technologies, and consequently the market for MEMS components and systems is expected to grow at a rapid pace in the future.

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